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ABSTRACT. The spectral analysis methods used for detecting water on celestial bodies are described, and the possible abundance of water on planets and stars are discussed. Schubert's theory of water erosion on the lunar surface is reconsidered, and the possible existence of ice and water on the moon is suggested. The current evidence of water abundances on other planets of the solar system is reviewed. Synthesis of water in a stellar atmosphere as a function of temperature and concentrations of component elements is examined. The existence of water on cool stars and in interplanetary space is quoted. The possible synthesis of water within the umbrae of sunspots is discussed. A71-26956

Water is one of the most important chemical compounds on earth for living /93* things of all kinds. Every reader knows from his own experience what significance water has for humans, animals and plants. Water - "in the chemical sense" a compound made from the elements hydrogen and oxygen, symbolically H_2O - is additionally very common and plays a significant role in the cycle of so-called inanimate nature owing to its special physical and chemical properties. Expansion occurring with freezing is decisive for many erosion phenomena. The very high energy of evaporation and thermal capacity have a compensatory balancing effect on the distribution of the sun's energy radiated on the surface of the earth. The dissolving capability of many salts is the precondition for salt deposits from oceans and bays.

It is therefore not surprising that even centuries ago the presence of water on extraterrestrial objects was presumed. The darker areas of the moon's surface were designated by the Latin name mare, i.e., sea. "Canals" were observed on the planet Mars and were thought to be filled with water by highly imaginative humans. The similarly conceived Mars' men were supposed to have built these hundred-kilometer wide trenches in order to supply their fields with precious water.

In order to test these hypotheses and look for water on extraterrestrial objects, astronomers had to avail themselves of scientific methods used for

* Numbers in the margin indicate pagination of the foreign text.

detection of water. Water can be chemically detected in the laboratory by its reactions, that is, by electrolytic decomposition into hydrogen and oxygen. Using the simplest of means, such as special silicates which become colored through absorption of water, fractions of a gram of water can easily be detected. In the field of physics, the absorption of electromagnetic radiation, i.e., light, radiowaves or X-rays, can be determined in water. In this case, various detection methods can be used depending on which range of wavelengths is appropriate for the absorption.

The oldest method is based on spectroscopy according to which water vapor is radiated by white light. The light from quite special wavelengths is absorbed by water molecules whereby the molecules make a transition from a lower to a higher energy state. The absorption is seen in the spectrum by dark lines. The water vapor in the earth's atmosphere causes many hundreds of water vapor absorption lines to be seen in the sun's spectrum. (Most lines in the sun's spectrum, however, have their origin in the absorptions owing to metals in the outermost layers of the sun. These are the Fraunhofer lines so designated by their discoverer.)

The absorption in longwave sectors (radio radiation) also plays a role of increasing importance in modern research for the detection of water. In this case, radio radiation, for example, is reflected off a planet and the reflected radiation measured. Changes in the property of the radiation, i.e., its polarization, allow conclusions as to the presence of water vapor. This detection method requires a powerful radio transmitter and a sensitive detection apparatus. In this way, however, it is possible to demonstrate the reflection of radio radiation on planets.

The methods described only enable detection of free water vapor or, as the case may be, free water. A great deal of water is, nevertheless, contained in crystals. In order to detect this water, chemical processes are usually required. We shall confine our further discussion to free water on extraterrestrial objects.

Where up to this time has free water been sought after and where has its existence been proven?

No water has been detected on the moon. The "seas" are absolutely dry and the astronauts who walked on the moon found no water. The "seas," relatively darker than their surrounding environment, are plains made from a basaltlike material. How the latter and the characteristic moon craters came to be, the astronomers hope to reveal through further exploration of the moon by astronauts and, later on, astronomers and geologists, or even better selenologists.

Even those who baptized the "seas" as such should have already known from their quite commonplace observations that the "seas" could not be filled with water. When a sea or an ocean is observed from a mountain top, it is possible to find the sun reflected in the water when certain observation conditions are satisfied, which take into account the angle of the sun, the direction of view, and the height of the observer above the water. This would also have been the case when observing the "seas" from the earth, but never did occur. According to a recent theory there is supposed to have been water following great meteorite showers and there possibly will be again. This water is supposed to be located several kilometers down under the surface of the moon and to have come up through the impact craters on to the moon's surface, and have created by erosion the riverlike rills of which there are over 100 on the moon. G. Schubert, Los Angeles, who developed this theory, has tested in laboratory experiments how water behaves when it is next to a vacuum. In this case, the evaporation takes heat from the water so that a layer of ice rapidly forms under which a large part of the water remains liquid. Nevertheless, in order to prove out this theory, drillings will have to be made on the moon and this is hardly possible in the next few years.

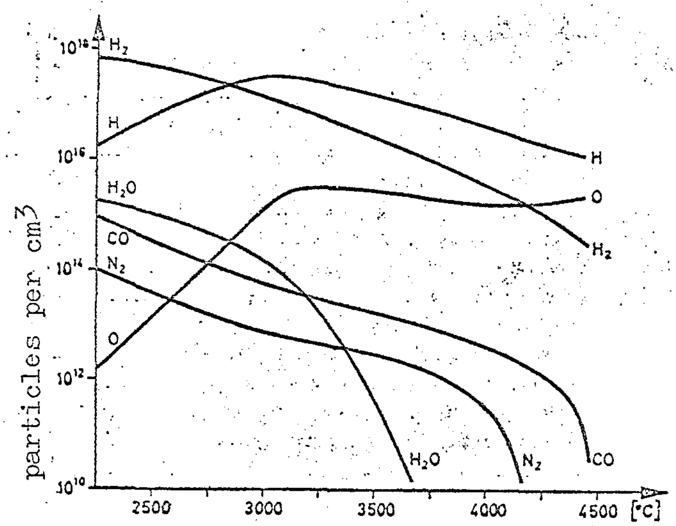
The remaining planets of our solar system have been intensively investigated for water. It is certain that nowhere does water play the dominant role is does on earth.

Mars is the planet which is most like earth. Its polar caps possibly arise from frost. The rapid changes in the expansion of these white caps at the north and south pole of Mars, possible to see with small telescopes, indicate that the frost layer is probably quite thin. It may be that the caps are made up from solid carbon dioxide which resembles snow at temperatures under -78°C (dry ice). The referenced "canals" are not discoverable for certain by means of the great telescopes and automatic probes with which Mars has been investigated. This is probably a matter of optical illusions of earlier observers - and by no means do they contain free water in great quantities.

Mercury, closest planet to the sun and quite like the earth's moon, likewise has no water on the surface. In addition, it probably has no atmosphere at all.

The planet Venus has also in past years been intensively investigated by means of artificial probes. It is quite mysterious owing to its impenetrable /9 cloud cover. Up to the present time, only carbon dioxide (CO_2) and carbon monoxide (CO) could be detected spectroscopically in its atmosphere. Small amounts of water were probably detected, owing to the change in polarization of the sunlight which it reflects. Water has also been detected on Mars by this method.

The largest planet, Jupiter, is presumed to have water in its atmosphere although a clear proof of this has not yet been made. Also, no free water has yet been detected on the other planets and their moons.



Concentration of some varieties of atoms and molecules in the atmosphere of a normal dwarf star with high-oxygen content (luminance class V).

By application of well-known laws of physics to the celestial bodies it can be theoretically calculated whether water is to be expected on a celestial body and how long it could have been there. Owing to thermal motion gas is always excaping from a celestial body. When the temperature is relatively slight, i.e., the thermal velocity accordingly low, a celestial body can retain gases for a longer time. In addition, the escape becomes more improbable with relative increase in mass and decrease in radius of the body. Since the water molecule is relatively light in comparison with other molecules ordinarily making up planet atmospheres, it makes its escape expecially fast from an atmosphere. It can be calculated that water on Mercury and the moon remains only a very short time in contrast to the age of these celestial bodies. On comparable masses of bodies further removed from the sun and hence colder, water is retained, on the other hand, for periods of time which are comparable with the age of the celestial body (several billion years).

Commencing with water on the earth a search for water should first be carried out on those celestial bodies more or less like the earth, e.g., the larger planets. After what was stated in the last paragraph concerning water in the atmosphere of celestial bodies, no water should be expected to be found on the planetoids which orbit around the sun between the orbital paths of Mars and Jupiter, since the former have much too small masses.

In some cases, disturbances of the orbits of other stars have led to the assumption of existence of planetlike satellites with these stars. It can also be presumed from the hypothetical scheme of the origin of our planetary system that similar systems exist around other stars. Up until now no planet has yet been detected around any star other than the sun. This should hardly ever be possible to do optically from the earth's surface since the brightness to be expected of the objects would be very slight. Speculation as to the presence of water on these unknown objects is therefore not very reasonable.

To look for water on extraterrestrial objects other than those resembling planets is likewise not very reasonable. The astrophysicist H. N. Russell, however, did show over 35 years ago that in the gas mixtures of chemical elements making up the sun's surface, at temperatures of 3000°C and less, the water molecule is one of the most common gas particles. Added to this a short theoretical observation, e.g., a so-called dynamic equilibrium prevails in gas mixtures which means that compounds are always being broken up and formed anew. The rates of decomposition and formation as well as the adjustments of equilibrium are a function of the temperature and the frequencies (concentrations) of the elements. The equilibrium adjustment can be calculated using the so-called law of mass effect of Guldberg and Waage

$$K(A) \cdot K(B)/K(AB) = F(T)$$

This equation states that the product of the concentration of the gases of elements A and B divided by the concentration of the gas of compound AB from elements A and B is a function of temperature.

The curves shown in the figure are supported by the work of Russell and recent publications. They show among other things the frequency of water as a function of temperature in a gas mixture similar to that prevalent on the sun. Since in addition to water there are still many other compounds which contain oxygen and hydrogen and all of which possess differing functions F(T), the sum of the frequencies of water, hydrogen and oxygen is not constant. Under 3000°C the water molecule is, as described, one of the most common particles in this gas mixture.

After many trials, G. Kuiper, the American astronomer, was finally able to detect water in the physically variable star Mira. Kuiper found water vapor absorption lines in the infrared spectrum range of 14,000 to 19,000 A. These lines increased in intensity as the star became colder. (The star Mira changes its brightness quite considerably in intervals of several hundred days. This physical change corresponds to a temperature change of the farthest outside layer of the star.)

In the past years water vapor has been detected spectroscopically on a number of "cool" stars, i.e., stars with surface temperatures under 4000°C.

A temperature of 5500°C prevails on the average on the sun. The water molecules are accordingly almost all decomposed. It is known from other spectroscopic observations that the elements oxygen and hydrogen are nevertheless present in great quantities on the sun. It would be possible for water to be formed in detectable quantities in cooler regions of the sun.

Actually, there are cooler regions on the sun. These are the sunspots in whose umbras the temperature often drops under 3000°C. In the spectrum of the umbras there are far more absorption lines than in the spectrum of the photosphere. This enables the conclusion, even without precise data, that compounds are present in the umbras which are not stable in the hotter regions of the sun. In accordance with the theoretical considerations of Russel and other astrophysicists there must be water present in detectable quantities in the umbras of the sunspots. The detection is not easy, however, owing to the strong lines of absorption of terrestrial water in the sun's spectrum. The spectroscopic searches carried out up until now for water in sunspots show that the terrestrial lines in the spectrum of the umbras become reinforced. The detection of water vapor in the umbras of sunspots, however, is not yet unequivocal. By observation from high-altitude research stations, where the terrestrial /95 concentration of water vapor is less, or with instruments enabling observations to be made from outside the atmosphere, it should soon be possible to unequivocally detect water in sunspots.

One brief estimate may shed light on the quantity of water on the sun, e.g. one large sunspot can have an area just as large as the earth's surface (approximately 500 million square kilometers). According to the data in the figure, one in every thousand particles in the gas corresponding to the umbras is a water molecule. Since the water molecule is relatively heavy in comparison with the otherwise more frequent particles, it can be assumed that barely 1% by weight of the sunspot material is water. From measurements and theoretical considerations it can with some degree of certainty be concluded that there is a mean density amounting to one-tenth of a millionth of a gram per cubic centimeter of the umbra material. The depth of a sunspot is assumed to be approximately 1000 km. It then follows that the mass of an umbra amounts to approximately $5 \cdot 10^{19}$ grams and the quantity of water to $5 \cdot 10^{11}$ tons. It amounts to less than one millionth of the quantity of water on the earth (approximately 10^{18} tons). Even in the case of maximum sunspot activity, when more than three pars pro mille of the sun's surface are covered by sunspots, the total amount of water reaches hardly a thousandth of that of water on the earth. Since the quantity of water on Mars and Venus and the other extraterrestrial objects in our planetary system is perceptibly less, it can be assumed that the sun is second in our planetary system only to earth as a principal carrier of free water.

In the last few years, astrophysical research has not only studied the stars and systems of stars, but also the space between the stars and the spiral nebulae, i.e., the interstellar and intergalactic space, and has continued involvement in the investigations on the space-time design of the world. It has been known for decades that interstellar space is not empty. It is filled with interstellar material which considerably changes in part the observed light of the stars. It has only been very recently that water vapor has been detected using radio astronomical methods in interstellar space in regions with highly ionized hydrogen (i.e. regions in which free protons are present). The frequency of the observed line is in the vicinity of 22 GHz, corresponding to a wavelength of 1.3 cm. The concentration of water in interstellar space is still uncertain. Also, concerning the significance of the detection of molecules in interstellar space - in addition to H_2O, for example, ammonia and the OH radical were found - in relation to the origin of stars from interstellar material, there are still no more precise ideas.

Some water is present on those most spectacular objects of the early history of astronomy, the comets. It is evaporated from ice crystals when the comet comes in the vicinity of the sun owing to the radiation of the sun, and through the head of the comet and its tail distributed in interplanetary space. The difference between what is apparent and what is real, which is often to be found in astronomy, becomes especially valid here. The comets were considered earlier to be harbingers of bad luck which could burn everything up with their tail. Now we know that they are relatively small and insignificant bodies in the planetary system and even contain water.